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LACUSTRINE TRACE FOSSILS AND ENVIRONMENTAL CONDITIONS IN THE EARLY MIOCENE ERMENEK BASIN, SOUTHERN TURKEY

Alfred UCHMAN[1], Wojciech NEMEC[2], Ayhan ILGAR[3] & Carlo MESSINA[4]

[1] *Institute of Geological Sciences, Jagiellonian University, Oleandry 2a, 30-063 Kraków, Poland, e-mail: alfred.uchman@uj.edu.pl*
[2] *Department of Earth Science, University of Bergen, 5007 Bergen, Norway*
[3] *General Directorate of Mineral Research and Exploration (MTA), 06520 Ankara, Turkey*
[4] *Department of Geological Sciences, University of Catania, 95129 Catania, Italy; presently at: Statoil Research Centre, Rotvoll, 7005 Trondheim, Norway*

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Abstract: The Early Miocene lacustrine succession of the Ermenek Basin, an intramontane graben in southern Anatolia, consists of hemipelagic, variably calcareous mudstones and pelagic marlstones densely interspersed with tempestite sandstone sheets, subordinate turbidite sandstone sheets and sporadic layers of evaporitic limestone. The marly lake was hydrologically closed and mainly no deeper than 10 m, with the mean fairweather wave base at 1.5 m and storm wave base around 5 m. The deposits abound in trace fossils, including *Vagorichnus* cf. *anyao* (its second recognized occurrence), endichnial ferruginous ribbons, large tubular structures, oblique cylinders, small discontinuous ridges, undulating ridges, planar wall structures and a range of other bioturbational features. The tempestites and turbidites show both pre-and post-event trace fossils, with recognizable mixed and transitional layers similar as reported from marine tempestites and turbidites. The trace fossils constitute an impoverished *Mermia* ichnofacies indicating a considerable environmental stress. The lake salinity fluctuated, and the stress factor is attributed to the extreme environmental conditions (increased salinity and unusual water chemistry) caused by episodes of brackishness due to decreases in rainfall and increases in evaporation. Freshwater conditions are indicated by benthic ostracods and mollusc shells in offshore mudstones and by gastropod shells in coastal coal deposits, whereas marly layers contain only the ostracod species *Miocyprideis glabra asulcata*, implying mesohaline to polyhaline conditions.

Key words: bioturbation, *Vagorichnus*, intramontane lake, tempestites, turbidites, Central Taurides.

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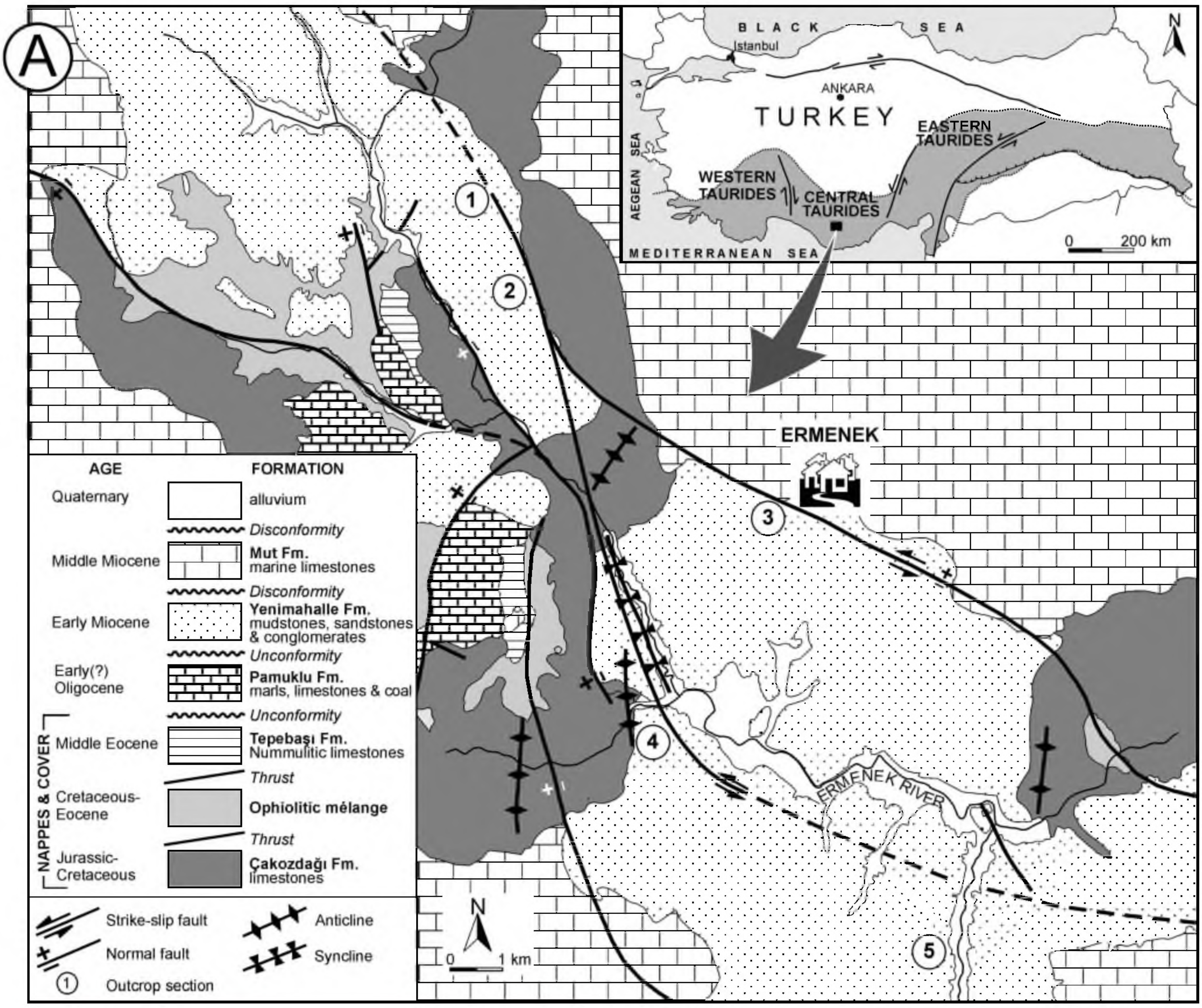
INTRODUCTION

The last decade has seen a rapid development of non-marine ichnology, including major advances in the documentation and understanding of ichnofauna assemblages in lacustrine sedimentary successions. Freshwater trace fossils, much like their marine counterparts, prove to be a useful tool for inferences about palaeoenvironmental conditions and a valuable source of proxy information on life forms in the geological past (e.g., Hasiotis & Bown, 1992; Donovan, 1994; Buatois & Mángano, 1995, 1998; Buatois *et al.*, 1998; Genise *et al.*, 2000, 2004; Hasiotis, 2002). However, the existing knowledge on freshwater ichnofauna is still little more than tentative, with more questions than answers and with many changes and corrections brought about by newer field studies. The ichnological documentation from lacustrine successions is particularly sparse, not only because such deposits are globally less widespread than marine ones, but also because lakes are not like "small seas" and their physicochemical conditions vary enormously (Lerman, 1978; Talbot & Allen, 1996; Carroll & Bohacs, 1999, 2001; Kevern *et al.*, 2004). The wide range of lacustrine environments obviously demands a comparably broad range of ichnological case studies.



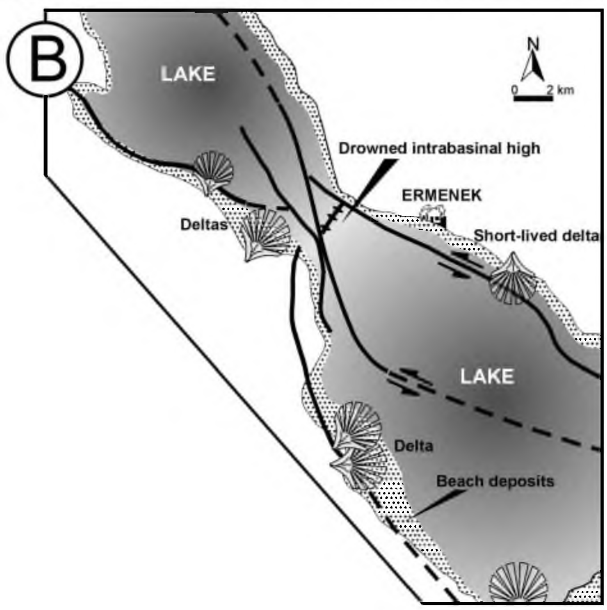


Fig. 1. Locality maps: **A** – Location of the Ermenek Basin in Turkey (inset map) and the basin's geological map; **B** – Early Miocene palaeogeography of the basin reconstructed for one of the lake-level highstands; the map depicts all the deltas involved in the lake history, although not all of them were coeval (for details, see Ilgar & Nemec, 2005)

The present study from the Early Miocene Ermenek Basin of southern Anatolia is a contribution to the knowledge on freshwater to brackish ichnofauna and pertains to an epoch and region thus far poorly explored by ichnologists. The lacustrine basin-fill succession, nearly 300 m thick, consists of alternating siliciclastic and calcareous deposits (Ilgar & Nemec, 2005) that abound in trace fossils, previously not studied. A systematic description and interpretation of the trace fossils is the main topic of the present paper, with particular attention given to the lake environmental conditions inferred from the sedimentary deposits.

GEOLOGICAL SETTING

The Ermenek Basin (Fig. 1A) is a Neogene intramontane molasse basin in the central part of the Tauride orogenic belt of southern Anatolia (Özgül, 1976; Dilek & Rowland, 1993; Gürer & Aldanmaz, 2002). The basin formed as a result of the orogen collapse in the extensional backarc regime of the Cyprean subduction arc to the south (Kempler & Ben-Avraham, 1987; Robertson, 2000). Bedrock consists of the Aladağ and Bozkır nappes, which were emplaced from the north in Late Eocene time (Andrew & Robertson, 2002). The nappes comprise Jurassic–Cretaceous limestones and a Late Cretaceous ophiolitic mélange, locally covered with Eocene shallow-marine limestones.

The allochthonous bedrock in the basin, strongly degraded by denudation, is overlain by Oligocene lacustrine carbonates, which are of small lateral extent and represent an incipient sedimentation in the evolving intramontane depression. This early period of "carbonate lake" sedimentation was interrupted by a late Middle Oligocene pulse of compressional deformation recording the last movement of the nappes, possibly gravitational, after which tectonic extension predominated and the structural framework of the basin was established.

The Ermenek Basin evolved as a SE-trending graben related to pre-existing fractures, oblique to the regional stress field of N–S crustal extension and affected by sinistral strike-slip deformation (Fig. 1A). Sedimentation resumed in the Early Miocene time, with two lakes merging into one and the intramontane depression becoming a large "clastic lake" (Fig. 1B; Ilgar & Nemec, 2005). Near the end of the Early Miocene, the isolated depression and surrounding bedrock terrain were abruptly inundated by a marine invasion, which covered the area with an extensive, thick succession of late Burdigalian–Serravalian limestones comprising reefal and platform facies. The former lacustrine basin is presently exposed in a wide valley of the Ermenek River (Fig. 1A), which incised throughout the carbonate cover in Pleistocene time.

BASIN-FILL STRATIGRAPHY

The pre-reefal sedimentary succession in the Ermenek Basin was originally described as a "Nummulite-bearing flysch", assigned an Eocene (Lutetian) age and referred to as the Yenimahalle Formation[1] by Gedik *et al.* (1979). Later, Tanar and Gökçen (1990) recognized that the Nummulite tests were redeposited, derived from bedrock erosion, and that the calcareous lower part of the succession contained well-preserved freshwater ostracods of Early Oligocene age. This evidence was confirmed further by Ilgar (2002).

The upper part of the pre-reefal succession, separated from the calcareous part by an unconformity, appeared to contain Early Miocene ostracods, including *Cyprideis torosa* Jones, *Candona candida* Müller, *Candona recta* Linenklaus and *Heterocypris salina salina* (Brady). Consequently, Ilgar (2002) referred to the Oligocene calcareous part of the succession as the Pamuklu Formation and retained the name Yenimahalle Formation for the Miocene upper part, from whose type section near the village of Yenimahalle in the basin's western part the name was originally derived. This lithostratigraphic terminology has been used by Ilgar and Nemec (2005) and is followed in the present paper.

The present study is concerned with the "clastic lake" period of sedimentation in the basin, represented by the Yenimahalle Formation – a succession of clastic lacustrine deposits, up to 300 m in thickness, including regressive deltaic wedges at the basin's southwestern margin and mainly non-deltaic shoreface wedges along the northeastern margin. The Yenimahalle Formation has a greater lateral extent than the calcareous Pamuklu Formation and hence overlies unconformably the latter and the surrounding bedrock (Fig. 1A; Demirel, 1989). The top of the Yenimahalle Formation is an abrupt transition to the fossiliferous, late Burdigalian–Serravalian marine limestones.

THE LAKE HISTORY AND SEDIMENTARY FACIES

The palaeogeography, sedimentary facies assemblages and sequence stratigraphy of the lake have been described in detail by Ilgar and Nemec (2005), with a focus on the basin's southwestern margin. The Early Miocene development of the basin commenced with alluvial sedimentation that led to the formation of two small lakes separated by midbasinal bedrock high. Shoal-water fan deltas prograded into these lakes from the southwest. The intrabasinal ridge resulted from transpressional tectonic deformation (Fig. 1A), and its southeastern flank initially hosted a peat-forming mire.

The two lakes gradually increased their volume, the midbasinal ridge was inundated and a large single lake formed, with the readvancing alluvial fans building Gilbert-type deltas. A solitary fan delta also prograded from the northeastern margin. This delta and two southwestern ones were subsequently drowned and permanently deactivated, probably by tectonic diversion of their feeder streams, while the remaining active deltas gradually retreated. The lake level along the southwestern margin then fell drastically, which caused fluvial incision and extensive subaerial denudation. Only one of the fluvial systems, in the southeastern corner of the basin (Fig. 1B), caught up with the escaping shoreline and formed a delta, probably because this stream had a larger drainage area. The other fluvial feeders formed alluvial fans that prograded across the emerged nearshore

1 The name Yenimahalle Formation used in the Ermenek Basin should not be confused with the identical name introduced by Akay *et al.* (1985) and used by others for the marine Pliocene deposits in the nearby Antalya Basin to the west

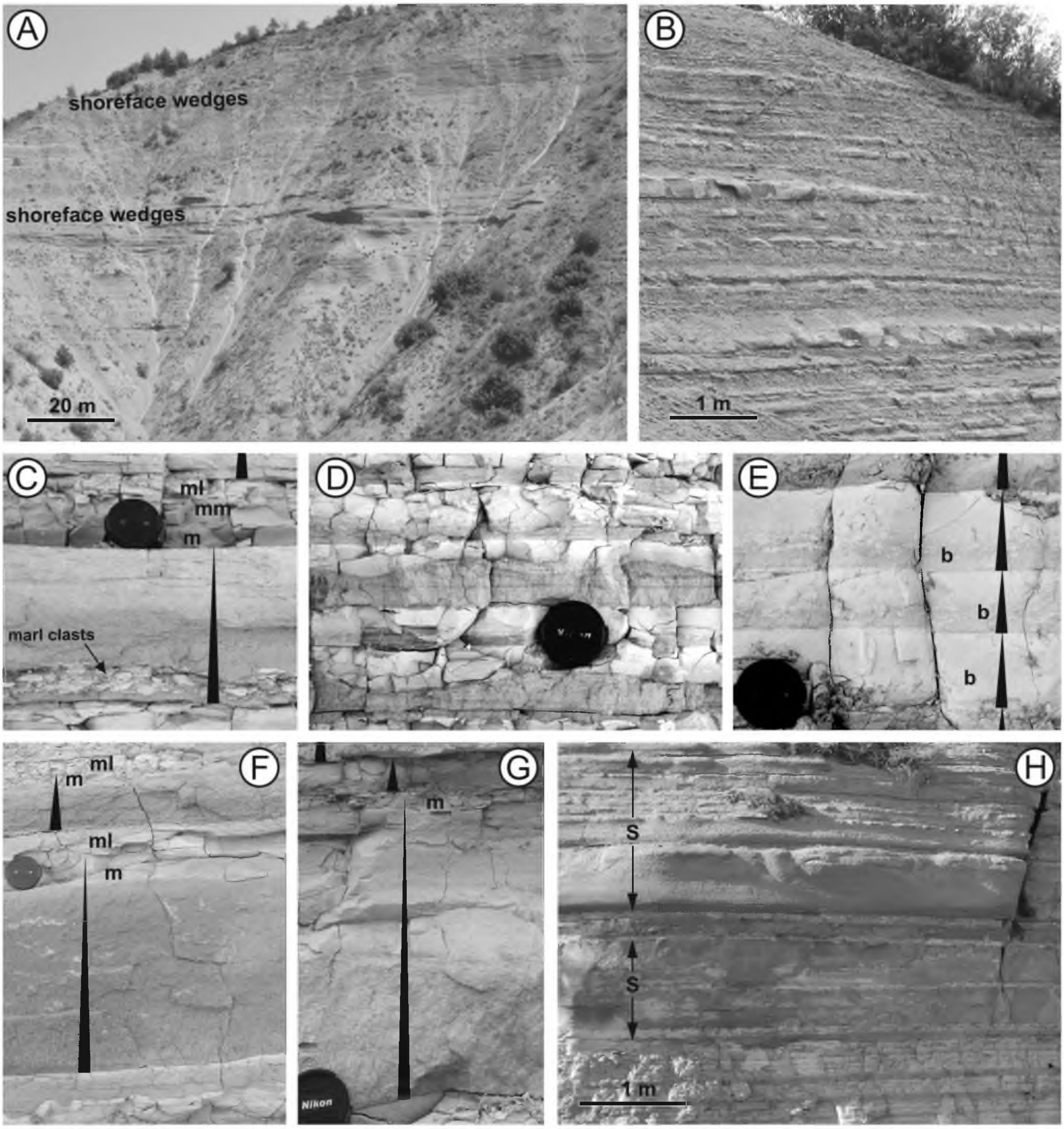


Fig. 2. Sedimentary facies of the lake interior: **A** – The upper middle part of the lake-fill succession at locality 1 (Fig. 1A), including two stratigraphic intervals with shoreface sandstone wedges up to 1.5 m thick; **B** – Sheet-like sandy tempestites and minor turbidites interbedded with mudstones and marlstones; outcrop corresponding to the upper mid-part of log A in Fig. 3; **C** – A graded sandy tempestite bed with marl clasts in the basal part and a sharp top overlain by mudstone (m), marly mudstone (mm) and marlstone (ml); **D** – Thin sandy tempestites embedded in marlstone; note their sharp bases and sharp tops with preserved wave ripple forms; **E** – Graded marlstone beds with silty, bioturbated (b) lower parts, attributed to the fallout of storm-derived suspension clouds; **F, G** – Sandy turbidites with sharp bases and gradational tops, overlain by mudstone (m) and marlstone (ml); **H** – Regressive wedges of planar parallel-stratified shoreface sandstones at locality 2 (Fig. 1A). The lens cap is 5 cm

zone. It is uncertain if this fall in water level briefly re-separated the lake into two parts, especially since no corresponding lake-level lowstand is recognizable along the basin's northeastern margin.

The lake level at the southwestern margin then rose again, with the active delta shifting laterally and one of the drowned alluvial fans evolving into an advancing delta. The subsequent fall of lake level along the margin left only one fan delta active, in the basin's southeastern corner, whereas the other alluvial fans prograded across the emerged near-shore zone and formed deltas as the lake level gradually rose again.

The next relative fall of lake level caused fluvial incision and subaerial denudation along the southwestern margin. The advancing alluvial fans were then abruptly inundated, forming Gilbert-type fan deltas, and this transgression culminated in the greatest expansion of the lake. The subsequent fall of lake level along the margin re-emerged the nearshore zone, with a lowstand alluvial wedge prograding at the coastal sites of fluvial activity. The late Burdigalian marine invasion from the south then rapidly inundated the basin and its mountainous surroundings, forming a large, semi-enclosed marine embayment dominated by biogenic carbonate sedimentation (Vrielynck *et al.*, 1997; Rögl, 1998; Atabey *et al.*, 2000).

The relative lake-level changes along the southwestern margin are difficult to correlate with those along the northeastern margin, where regressive shoreface wedges are recognizable only in the upper half of the lake-fill succession (Fig. 2A, H). Cross-basinal outcrop sections are discontinuous, cut by faults and lacking correlative markers. The northeastern margin was a high-relief bedrock coast with a perched narrow belt of beach deposits (non-preserved) and a sandy shoreface zone. The shoreline there would have a steep migration trajectory (Helland-Hansen & Martinsen, 1996) and hence be less responsive to moderate lake-level changes.

Although regional climatic changes are considered to have been the main factor controlling the lake facies and water-level changes, it is likely that the tectonic subsidence of the graben floor involved some asymmetrical seesaw-like movements, which would explain further the apparent lack of correspondence in shoreline regressions at the opposing margins of the basin (see discussion by Ilgar & Nemec, 2005). Episodes of strike-slip movement (Fig. 1A) could have contributed to asymmetrical subsidence.

The whole central, main part of the basin – from which most of our ichnofauna evidence derives – contains sheet-like sandstone and siltstone beds alternating with mudstones (variably calcareous), marlstones and sporadic limestone layers (Fig. 2B). Sandstones are whitish to yellowish grey in colour and form extensive tabular beds of two types. The sandstone beds of predominant type are very fine- to medium- grained, generally well sorted and 1 to 35 cm thick, with erosional and commonly loaded bases and also with sharp upper boundaries – planar, undulatory or rippled (Fig. 2C, D). These beds show normal grading, planar parallel stratification, wave-ripple cross-lamination and sporadic swaley or hummocky stratification (Fig. 3). Their basal parts are commonly massive and/or contain scattered intraformational clasts (Fig. 2C). The sandstone beds of second type are fine- to coarse-grained (locally pebbly) and moderately sorted, 5–45 cm thick, with sharp bases and gradational upper boundaries, and internally showing current-ripple cross-lamination, commonly underlain by planar parallel stratification with or without a basal massive division (Fig. 2F, G).

The associated siltstone beds are very thin (0.5–1.5 cm), parallel laminated or ripple cross-laminated, often composed of more-or-less isolated ("starved") wave-ripple lenses. Mudstone beds are 1–25 cm thick and commonly calcareous or transitional to marlstone. They are dark- to light-grey and generally massive, but contain streaks and thin lenses of silt or very fine sand attributable to wave-generated, starved "rolling-grain" ripples (Sleath, 1976; Harms *et al.*, 1982). Marlstone beds are up to 90 cm thick (Fig. 3A), whitish or yellowish grey and commonly composite, comprising graded layers with silty to muddy basal parts and abundant burrows (Fig. 2E). Calcareous horizons include isolated beds of micritic limestone, some of which are up to 1 m thick and extend into the lake-margin shoreface facies zone, but commonly also pinch out towards the lake centre (Ilgar & Nemec, 2005). The marlstone and limestone beds have gradational contacts with the underlying mudstones, are non-fossiliferous and lack evidence of biogenic origin.

This assemblage of sedimentary facies is considered to represent the lake offshore environment dominated by mud suspension fallout and punctuated by episodic emplacement of sand and silt sheets below fairweather wave base (Ilgar & Nemec, 2005). Similar deposits have been described from the offshore areas of relatively shallow, wave-dominated lakes (e.g., Duke, 1984; Eyles & Clark, 1986; Dam & Surlyk, 1992, 1993). The sandstone and siltstone beds with sharp bases and tops and with wave-formed structures are interpreted to be tempestites, deposited by storm events (Dott & Bourgeois, 1982; Hunter & Clifton, 1982; Arnott & Southard, 1990; Duke, 1990; Dumas & Arnott 2006). The sandstone beds with gradational tops and unidirectional flow features are attributed to delta-derived turbidity currents, probably generated episodically by hyperpycnal stream effluent (Gilbert, 1975; Mulder *et al.*, 1998). Tempestites predominate throughout the basin, particularly in its whole northeastern part (Fig. 3A), whereas turbidites occur mainly in the southwestern to central part, in the neighbourhood of deltas (Fig. 3B). The siliciclastic mud was derived from land (hemipelagic sediment) and spread by storms and turbidity currents, whereas the non-biogenic carbonate material was apparently produced in the lake water (pelagic sediment).

INTERPRETED LAKE CONDITIONS

The elongated lake during its water-level highstands was nearly 13 km wide and 45 km long (Fig. 1B), which

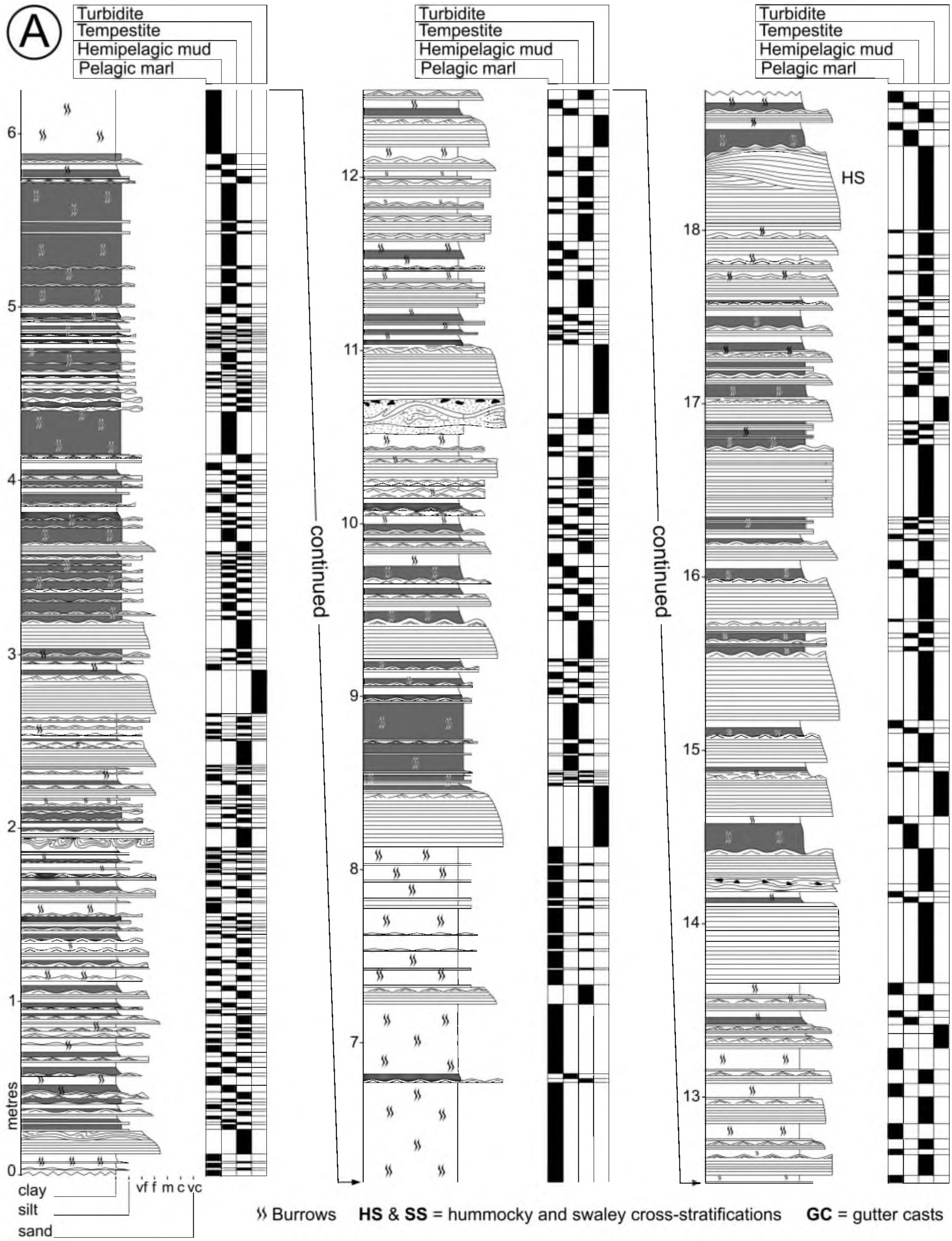


Fig. 3. The main sedimentary facies of the lake interior and their interpretation (continuation in the next page): **A** – Portion of a detailed sedimentological log from the north-central part of the basin (locality 1 in Fig. 1A), where tempestites predominate; **B** – Portion of a detailed log from the proximity of a delta in the basin's southeastern part (locality 4 in Fig. 1A), where also turbidites are common

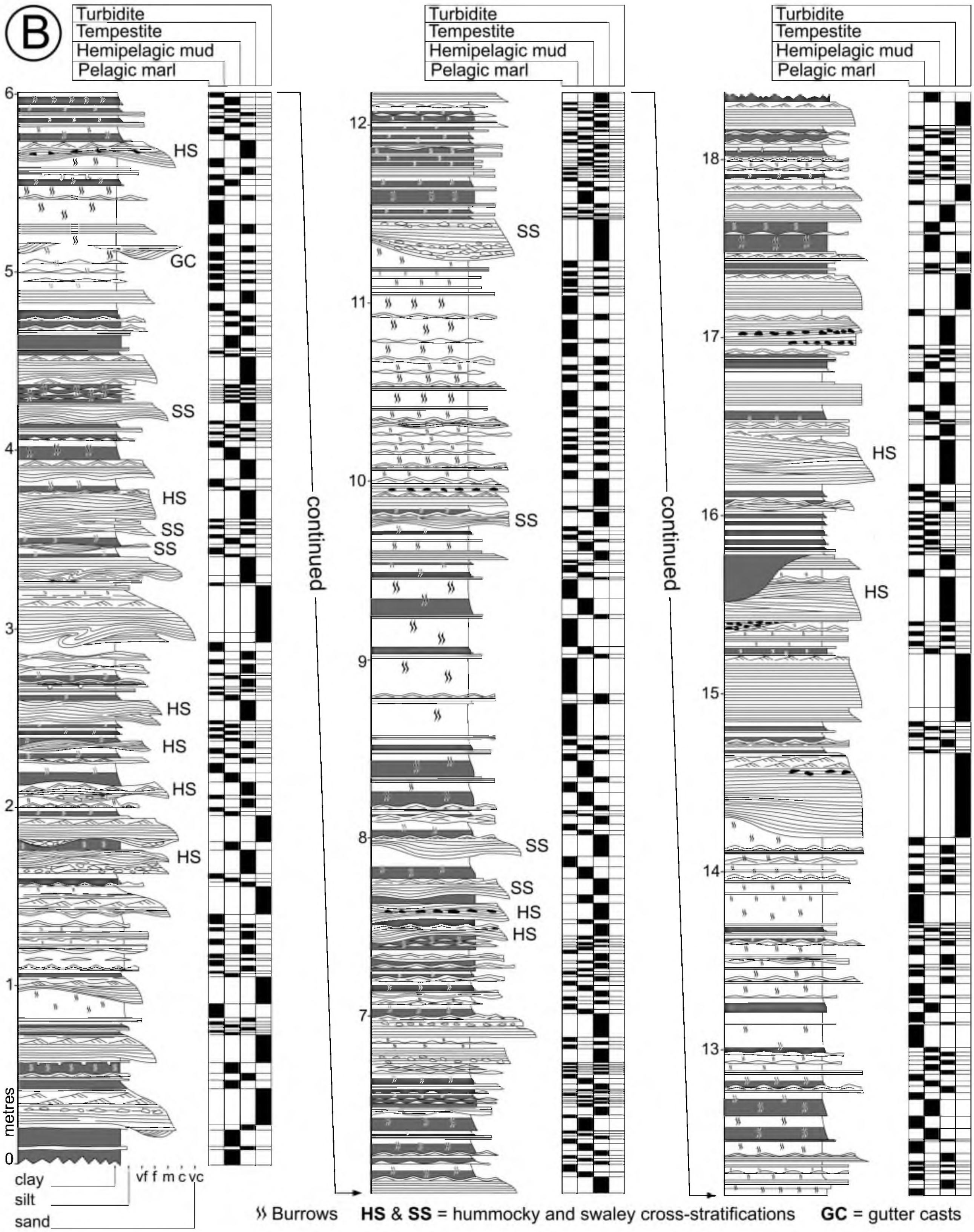


Fig. 3. Continuation from the former page

would have provided a considerable wave fetch for strong winds parallel to the graben axis. The thicknesses of Gilbert-type deltas, corrected for sediment compaction, indicate that the lake was mainly no deeper than 10 m and exceeded slightly a depth of 20 m in its southeastern part only during the greatest highstand (Ilgar & Nemec, 2005, fig. 9). The thicknesses of normal-regressive shoreface wedges in both the southeastern and the northwestern part (Fig. 2A) suggest a mean depth of fairweather wave base around 1.5 m, whereas the thicknesses of associated offshore-transition deposits allow the mean depth of storm wave base to be estimated at around 5 m. According to these estimates, the mean wavelengths of fairweather and storm waves would appear to be around 3 and 10 m, respectively, and the period of storm waves would be about 2 sec (see Allen, 1997, eq. 8.26). The storm waves in the offshore-transition zone were not breaking and their height must thus have been less than 1/12 of the wavelength, which means below 80 cm (Allen, 1997, p. 296). The wavelength of storm-generated ripple forms in offshore-transition deposits is typically around 13 cm (Fig. 2D), which implies orbital diameters of ca. 20 cm for the motion of water particles near the lake floor (Allen, 1997, eq. 8.35).

High bedrock topography separated the Ermenek Basin from the adjacent Mut Basin about 90 km to the east, where concomitant alluvial sedimentation occurred. The intramontane lake is thus considered to have been hydrologically closed, probably varying between underfilled and balanced-filled (*sensu* Carroll & Bohacs, 1999).

The Early Miocene regional climate was mainly humid, as is indicated by stream-dominated alluvial fans and peat accumulation, but significantly fluctuated. Late Neogene high-frequency climatic fluctuations attributed to astronomical forcing have been widely recognized in the Eastern Mediterranean (e.g., Postma *et al.*, 1993; Krijgsman, 1996; Postma & Ten Veen, 1999; Steenbrink *et al.*, 1999, 2000; Abdul Aziz *et al.*, 2000). Freshwater conditions in the lake are indicated by the benthic ostracods and mollusc shells in offshore deposits, and by gastropod shells in coastal coal beds (Ilgar, 2002). The lake-fill succession lacks evaporates, such as gypsum, but the lakewater salinity was episodically elevated. Some of the offshore marly beds contain only the ostracod subspecies *Miocyprideis glabra asulcata* Bassiouni, indicating mesohaline or possibly polyhaline conditions (i.e., water salinity higher than 3%, possibly in excess of 18%). The episodic brackishness suggests a decrease in rainfall and increase in evaporation.

The lake belongs to the category of "marl lakes" of Kevern *et al.* (2004). As discussed by the latter authors, such lakes are generally unproductive, yet may be subject to summer-time depletion of dissolved oxygen in the bottom waters and have very shallow Secchi disk depths, particularly in the late spring and early summer. These lakes receive significant amounts of water from springs at the lake bottom, and this mode of water supply will be particularly effective in high-relief drainage basins, where it may virtually predominate during the climatic periods of reduced rainfall. As the rainwater percolates through organic soils, it loses its dissolved oxygen to bacteria, derives CO_2 from bacterial respiration and increases its acidity, thus dissolving limestone bedrock. When the acidic, oxygen-poor and CO_2-supersaturated water enters the lake as groundwater, the excess carbon dioxide is given off to the atmosphere and the dissolved $CaCO_3$ becomes precipitated in the lake water, forming marls, limestone layers or simply adding carbonate to hemipelagic mud suspension. The importance of this process would vary with regional climatic fluctuations.

The water drained from limestone-rich catchment was probably hard, rich in calcium ions, and the lake was apparently prone to carbonate precipitation even during episodes of coastal inundation and minimum sediment supply. No isotopic data are available, but the isolated limestone layers are considered to be products of inorganic precipitation, possibly with non-calcareous plankton blooms as a triggering factor (see discussion by Ilgar & Nemec, 2005).

SYSTEMATIC ICHNOLOGY

The following description of trace fossils is based on outcrop specimens and close-up photographs, with some of the former presently housed at the Institute of Geological Sciences of the Jagiellonian University, Kraków (collection label prefix 186P). The data are from the lower middle part of the lake-fill succession at locality 3, the middle to upper part at locality 1 and the uppermost part at locality 2 (Fig. 1A). The deposits at the latter locality a nearshore variegated calcareous mudstones and marlstones interspersed with thin tempestite sandstone sheets, whereas the two other outcrop sections show typical lake-interior deposits (Figs 2B, 3A).

Ichnogenus *Vagorichnus* Buatois, Mángano, Wu et Zhang 1995

Diagnosis: Complex three-dimensional burrow system consisting of discontinuous curved to meandering segments and ridge-like knobs, which form irregular networks (according to Buatois *et al.*, 1995).

Type ichnospecies: *Protopaleodictyon anyao* (Wu, 1985).

Remarks: *Vagorichnus* and its only ichnospecies *V. anyao* (Wu, 1985) were described from the Early Jurassic lacustrine turbidites of the Anyao Formation, Henan Province, central China, and were interpreted as an actively filled invertebrate feeding structure (fodinichnion) preserved in full relief (Buatois *et al.*, 1995). For comparison, the mostly deep-marine *Megagrapton* Książkiewicz 1968 and *Protopaleodictyon* Książkiewicz 1970 are similar, but forming continuous networks or meanders with appendages, respectively, and interpreted as open burrow systems (e.g., Uchman, 1998). They are preserved mostly as hypichnial semi-reliefs. The *Labyrintichnus* Uchman & Álvaro 2000 described from the non-marine Miocene deposits of the Teruel Basin, Spain, is also similar to *Vagorichnus anyao*, but represents an open burrow system with many branches. It cannot be precluded that *Vagorichnus* Buatois *et al.* 1995 is a junior synonym of *Multina* Orłowski 1968 at the ichnogenus level (Uchman & Álvaro, 2000), similarly as *Pseudopaleodictyon* Pfeiffer 1968 and *Olenichnus* Fedonkin 1985. The type material of all their type ichnospecies should be carefully examined to resolve this issue.

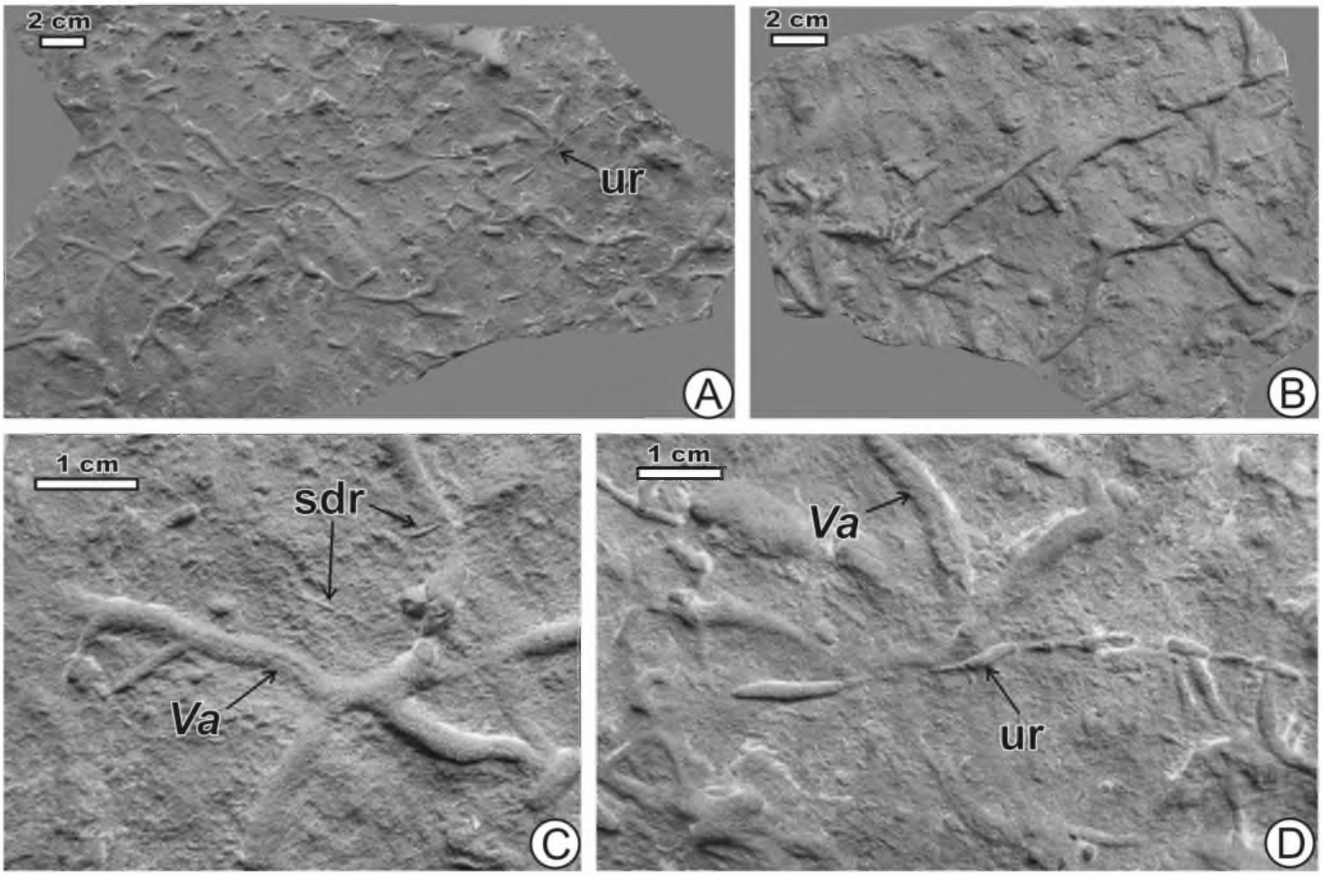


Fig. 4. Hypichnial trace fossils from sandy offshore-transition tempestites at locality 1 (Fig. 1A): **A** – *Vagorichnus* cf. *anyao* (Wu, 1985) and an associated undulating ridge (ur); specimen 186P1; **B** – *Vagorichnus* cf. *anyao* (Wu, 1985); specimen 186P2; **C** – Close-up detail of specimen 186P1, showing *Vagorichnus* cf. *anyao* (Wu, 1985) (Lt) and associated small discontinuous ridges (sdr); **D** – Another detail of the same specimen, showing *Vagorichnus* cf. *anyao* (Wu, 1985) with a slightly bilobate ridge (Vab) and associated undulating ridge (ur)

Vagorichnus cf. *anyao* (Wu, 1985)
Fig. 4

Description: Hypichnial, semi-cylindrical ridges forming an irregular network. The ridges are 2.5–3.0 mm wide, smooth and slightly winding, locally flattened to weakly bilobate and commonly discontinuous. They are crossing one another and show Y-shaped branches, with the distances between the branching points from 25 to 60 mm. The ridges are associated with knobs of a comparable width and extend over a narrow vertical range of levels. They terminate by descending gradually towards the bedding plane, or by ascending and breaking into short blind cylinders slightly above the bedding plane. The ridges are preserved in semi-relief in fine-grained, ripple cross-laminated, brownish-grey sandstone tempestites 2–3 cm thick. The sandstone beds have uneven soles, and the laminae in their uppermost parts are commonly rich in fine plant detritus. A semi-relief preservation of burrows is evidenced by the welding of ridges and their apparent continuity along a bedding plane, whereas full relief can be observed only in vertical cross-sections.

Remarks: The trace fossil described above is interpreted as a washed out and cast burrow system similar to *Vagorichnus anyao*. The evidence may support the notion of an actively-filled burrow system that was exhumed and had its infill washed out by storm-generated currents prior to casting. However, the blind termini of the ridges ascending above the bedding plane may indicate an open subsurface burrow system produced in mud and subsequently scoured and cast with sand during the storm event. Although most of the type material of *V. anyao* shows preservation as hypichnial, actively-filled full reliefs (Buatois *et al.*, 1995), some of the samples (collection housed in the Department of Resources and Environmental Engineering, Henan Polytechnic University in Jaozuo, China) include hypichnial ridges welded with the turbidite sole without any discontinuity (Fig. 5) (A. Uchman, unpublished data, 2005; confirmed by Zhang Guocheng, personal information, 2007). It would thus appear that *V. anyao* can be preserved in full- and semi-reliefs, and may represent burrow systems formed at different depths beneath the lake floor. Semi-reliefs can result from the collapse of sand into grooves produced by the tracemakers at the mud-sand interface (see Jensen & Atkinson, 2001).

The type material of *V. anyao* shows common flattened ridges, but no tendency for the local development of bilobate geometries (Wu, 1985). Furthermore, the transitions to *Gordia* Emmons 1844 and the vertical undulations observed in *Vagorichnus* (Buatois *et al.*, 1995) are lacking in the present case. These facts, together with the atypical preservation mode and the lack of significant vertical undulations and a tendency for looping, compel us to keep the trace's name open, at the ichnospecies level (hence the suffix "cf." in the taxonomic label).

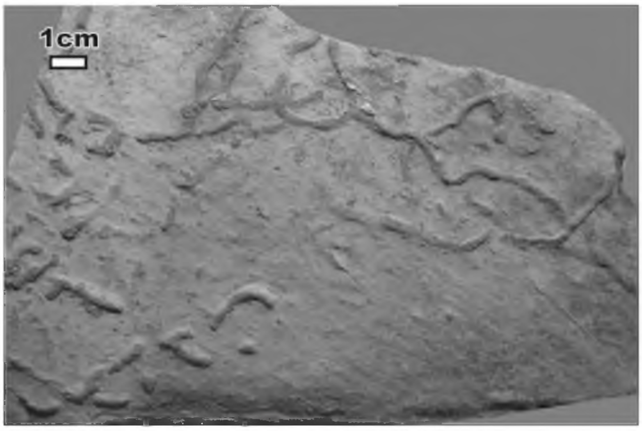


Fig. 5. *Vagorichnus anyao* (Wu, 1985) from the Early Jurassic Anyao Formation, Henan Province, China. Sample for comparison (*cf.* Fig. 4); from collection at the Department of Resources and Environmental Engineering, Henan Polytechnic University in Jaozuo, China

Similar bilobate hypichnial ridges are produced by marine amphipod *Haustorius arenarius* Slabber on mud-sand interfaces, as shown experimentally by Jensen and Atkinson (2001). It is possible that also non-marine amphipods produce similar structures, including *Vagorichnus*.

Undulating ridges
Fig. 4A, D

Description: Hypichnial, slightly winding ridges up to 1.5 mm in width, with traceable lengths of up to about 70 mm. The ridges are preserved in full relief in some of the sandy tempestites bearing *Vagorichnus* cf. *anyao*, locally cross-cutting the latter trace fossil. They are slightly undulating with respect to the bedding plane, with their elevated segments, 3–12 mm long, appearing on the bedding plane as elongate mounds 10–25 mm apart, plunging longitudinally into the sandstone bed in both directions.
Remarks: The undulating ridges are similar to the trace fossil described by Buatois *et al.* (1996) as *Tuberculichnus vagans* Książkiewicz 1977 from the Early Jurassic lacustrine deposits of Central China. However, a range of trace fossils of different ichnogenera appeared to have been lumped under the label *Tuberculichnus* Książkiewicz 1977, and the ichnogeneric affiliation of *Tuberculichnus vagans* has meanwhile been changed to *Protovirgularia* McCoy 1850 (see Uchman, 1998). Notably, the original material of *Protovirgularia vagans* shows a strongly carinate morphological profile of the trace fossil (Uchman, 1998), whereas this feature is not recognizable in the present case.

Small discontinuous ridges
Fig. 4C

Description: Hypichnial, curved or straight ridges, slightly winding and only up to 1 mm wide, with traceable lengths of up to 15 mm. The ridges are associated with knobs of a comparable size. Some of the ridges are cross-cutting the semi-relief of *Vagorichnus* cf. *anyao*, which indicates their preservation in full relief.
Remarks: This trace fossil is difficult to ascribe to any established ichnotaxon. The ridges were probably produced by the burrowing and possibly grazing activity of some very small invertebrates.

Endichnial ferruginous ribbons
Fig. 6

Description: Endichnial, horizontal to slightly oblique and gently winding ribbons, 1.0–3.5 mm wide, preserved in full relief in cross-laminated marly siltstone. The individual ribbons have uniform widths, show local Y-shaped branches and are covered with ferruginous fine-grained sandstone of the overlying tempestite bed. The ferruginous staining of sediment may represent oxidized organic matter. This trace fossil has been found only in the variegated, marl-rich deposits of lake-margin embayment (locality 2 in Fig. 1A).
Remarks: The endichnial ribbons seem to be the flattened tunnels of a burrow system, rather than plant-root casts, because they have uniform widths and plunge gently across the sediment lamination in a wide range of directions. It cannot be precluded that at least the larger forms are a full-relief preservation variety of the *Vagorichnus* cf. *anyao* described above, with its open tunnels collapsed. Unfortunately, this suggestion cannot be verified here, because the three-dimensional geometry of the endichnial ribbons is insufficiently visible.

Large tubular structures
Fig. 7A

Description: Hypichnial, flat and straight horizontal ridges, about 15 mm wide; rather poorly preserved and probably branching.
Remarks: The poor preservation does not allow for closer determination. It is possible that this trace fossil represents crustacean (crayfish?) burrows.

Oblique cylinders
Fig. 7B

Description: Oblique and nearly straight cylinders, 2.2 mm in diameter, formed in a marl and filled with sand of the overlying tempestite bed. Some of the cylinders extend in depth for about 28 mm below the overlying sandstone bed. The cylinders have sharp margins and at least one shows a whitish halo. Their termination pattern is unknown.
Remarks: The material is insufficient for closer determination. The cylinders were probably open burrows, and the white halo could have resulted from secondary oxidation around the burrow infill.

Planar wall structures
Fig. 7D

Description: Endichnial, planar wall-like structures in bioturbated, light reddish-brown marlstone beds, found in the lake-margin embayment at locality 2 (Fig. 1A). The wall features consist of whitish marl and are about 4.5 mm wide, 14–16 mm deep and at least 85 mm long. In a vertical cross-section, the wall in the middle of its height is slightly wider and its lower margin is rounded in shape. In a bedding-parallel plane, the trace fossil shows a single calyx-like widening (Fig. 7D).
Remarks: These are probably burrows of bivalves ploughing through cohesive sediment. The calyx-like widening can be a trace of the cleft bivalve foot anchoring in the sediment, as in the *Protovirgularia* McCoy 1850, which is a bivalve crawling trace (Seilacher & Seilacher, 1994). The trace fossil's overall shape resembles *Teichichnus* Seilacher 1955, although the spreiten typical of this ichnogenus are lacking here.

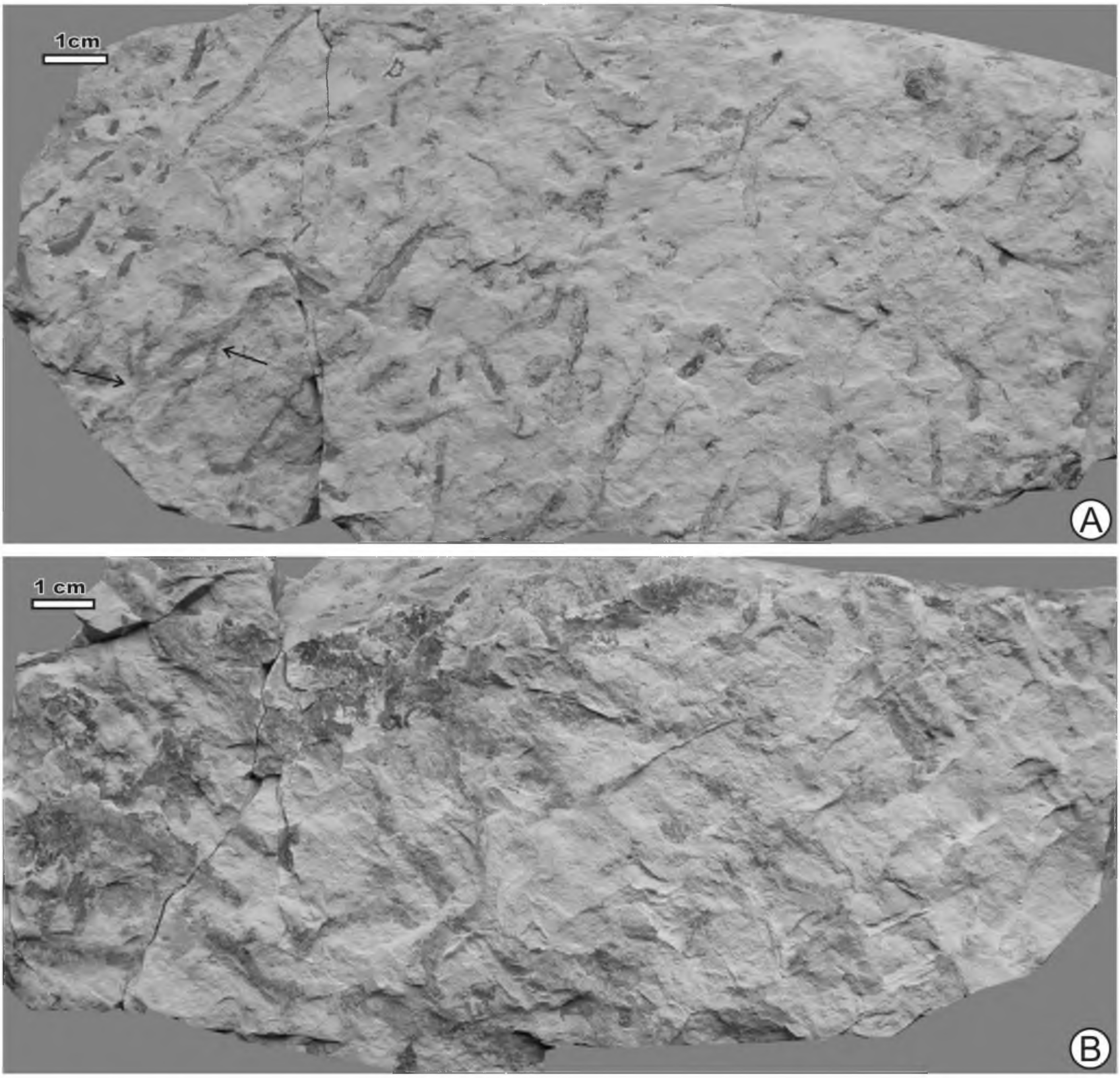


Fig. 6. Endichnial ferruginous ribbons in neashore sandy tempestites at locality 2 (Fig. 1A); specimen 186P6: **A** – Upper surface of sample, with the arrows indicating the branching points; **B** – Lower surface of the sample

Other bioturbation structures
Fig. 8

Description: Various endichnial tunnels 2–4 mm wide and clumps 2–12 mm wide, developed in a silty marlstone or sandy to silty mudstone and filled with finer-grained calcareous (marly) sediment. All these structures occur in graded marlstone beds (Fig. 8A) and in the mudstone layers capping sandy tempestite beds (Fig. 8B–D).

Remarks: The tunnels can be traced for only a very short distance and hence their closer determination is impossible. The clumps have irregular shapes and suggest an early-stage deformation of soft, fresh sediment. The clump margins are uneven, and their cross-sections suggest activity of oval amoeboid bodies. The tunnels and clumps were probably produced by different animals burrowing the silty sediment deposited from suspension directly after a storm event.

Void tubes
Fig. 9

Description: Endichnial, branching void tubes with a width range from < 1 mm to 4 mm and varied orientation, commonly vertical or oblique to the bedding plane. They occur in a marlstone bed, 3.5 cm thick, in the uppermost part of the variegated lake-margin deposits at locality 2 (Fig. 1A), below the transgressive marine limestones. The tubes are up to 15 mm long and their margins are commonly corroded (Fig. 9A).

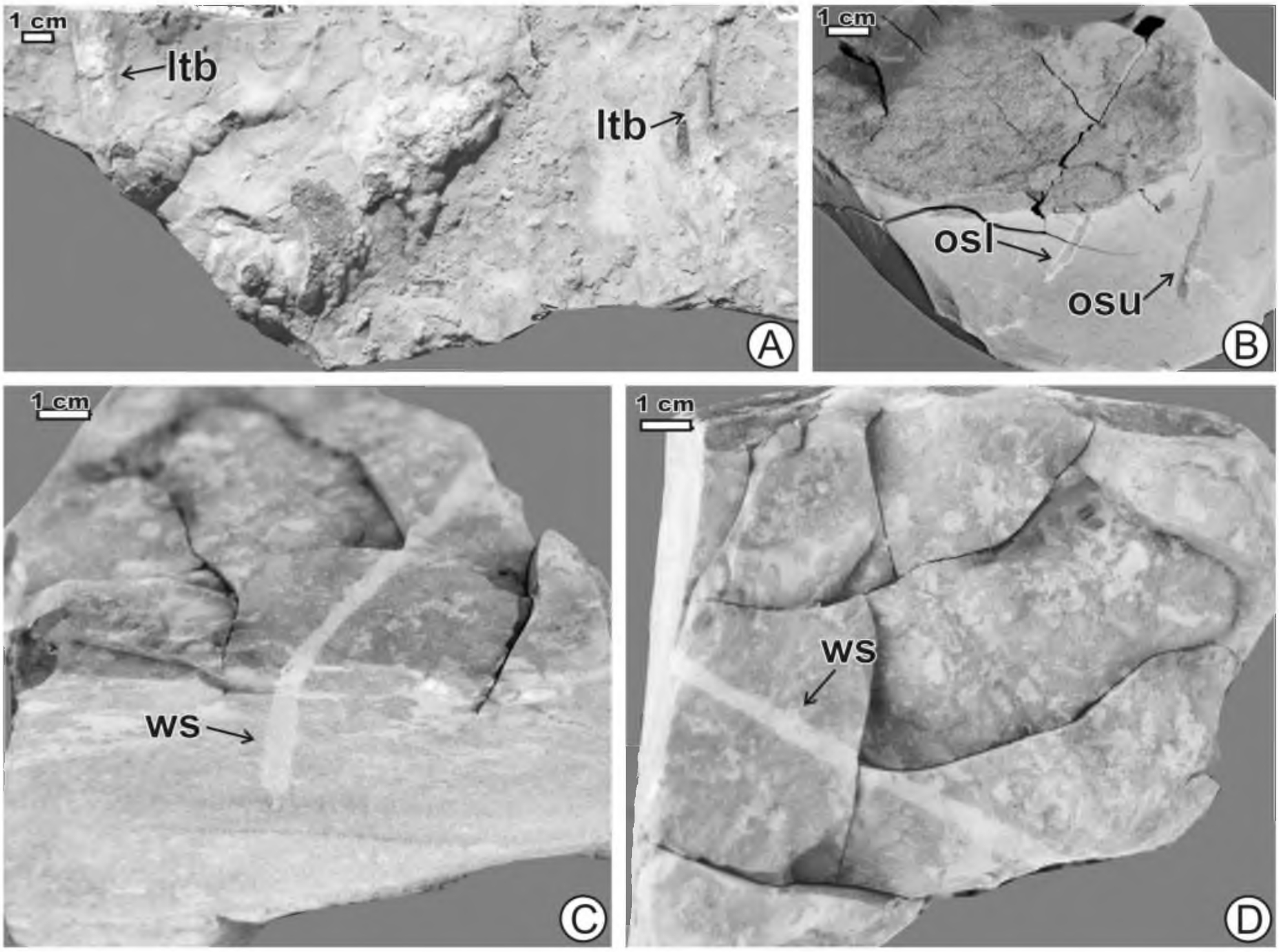


Fig. 7. Other trace fossils from the lacustrine succession: **A** – Large tubular structures (ltb); locality 1; **B** – Oblique cylinders with (osl) or without a halo (osu); locality 2; **C, D** – Wall structure (ws) and other bioturbation features at a bed top in an oblique and a downward view, respectively, with the arrow in D indicating a calyx-like widening; locality 2 (Fig. 1A)

Remarks: The tubes are not collapsed, which suggests rapid consolidation of the calcareous sediment, but are not filled with cement. The smaller of these features are similar to the "small tubular cavities" described by Melchor *et al.* (2002) from an incipient calcareous palaeosol in Eocene lake-margin deposits of Argentina. The void tubes in the present case may be burrows of small invertebrates or casts of oxidized, rotten plant roots. It also cannot be precluded that this trace fossil derives from incipient marine conditions, as it occurs at the stratigraphic transition to the marine carbonate deposits.

DISCUSSION

The trace fossils in the present study derive from two different subenvironments of the Early Miocene lacustrine basin. The *Vagorichnus* (Fig. 4), the undulating ridges (Fig. 4A, D) and small discontinuous ridges (Fig. 4C) are from the offshore-transition tempestites in the middle to upper part of the lake-interior succession. The other trace fossils (Figs 6–8) are from the marl-rich variegated uppermost part of the lacustrine succession in a lake-margin embayment. Both these subenvironments were dominated by "event" sedimentation, with the background suspension fallout punctuated by frequent episodes of sand or silt incursion. These discrete episodes in the lake interior area were storm action and sporadic turbidity currents (Fig. 3), whereas the shallow lake-margin embayment was subject to only modest storm waves.

The sheet-like tempestite sandstone beds in the lake interior (Fig. 2B) show evidence of pre- and post-event colonization by fauna, as is also typical of marine tempestites (e.g., Frey & Goldring, 1992; Pemberton *et al.*, 2001). Pre-event ichnofauna includes *Vagorichnus* and possibly some of the small discontinuous ridges preserved as scoured and cast burrows on the tempestite soles. The post-event trace fossils include the undulating ridges and most of the small discontinuous ridges, preserved in full relief on the tempestite soles and representing animal burrowing beneath the storm-event deposit. The storm deposits and sporadic

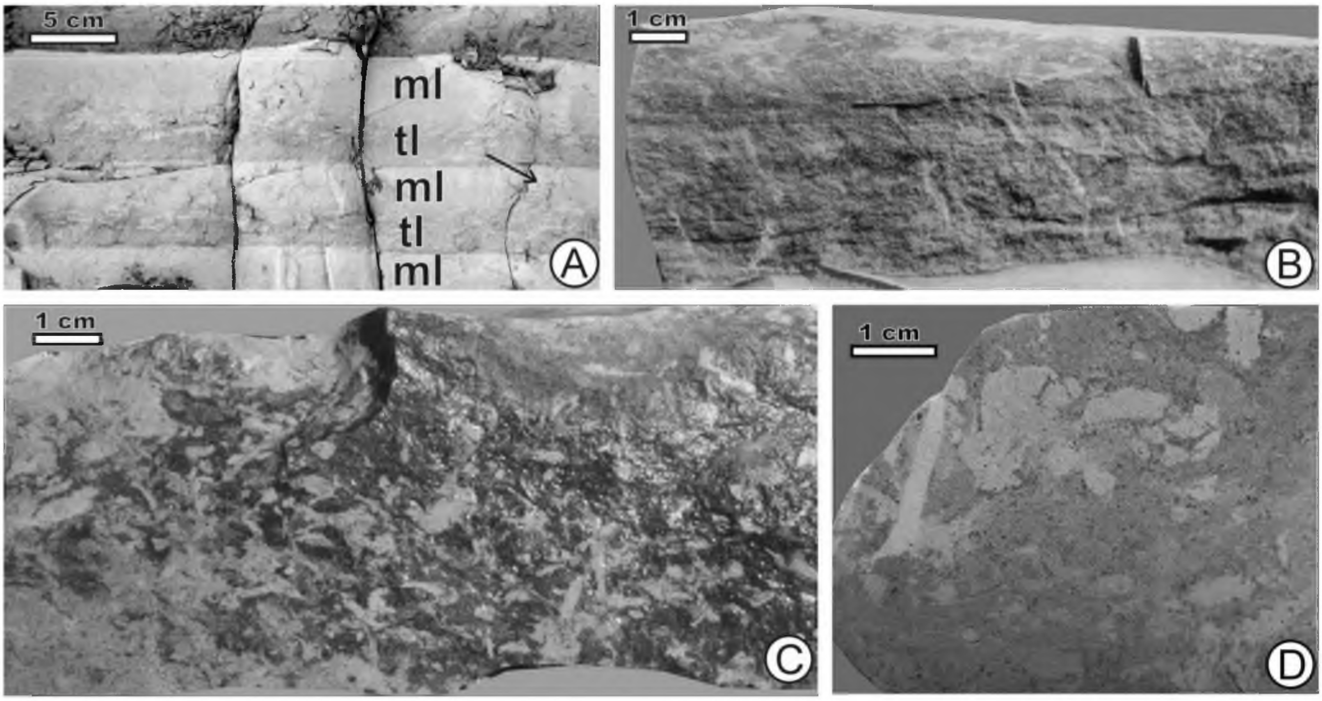


Fig. 8. Unspecified other bioturbation features in the lacustrine succession: **A** – The mixed (ml) and transitional layers (tl) in silty tempestites grading into "background" marlstones, locality 1; **B** – Bioturbation features in the muddy cover of a fine-grained, cross-laminated sandy tempestite, locality 1; **C** – Bioturbation features on the muddy top surface of a very fine-grained sandy tempestite, locality 2; **D** – Bioturbational structures on a bedding-parallel polished surface of fine-grained sandy tempestite, specimen 186P3 from locality 2 (Fig. 1A)

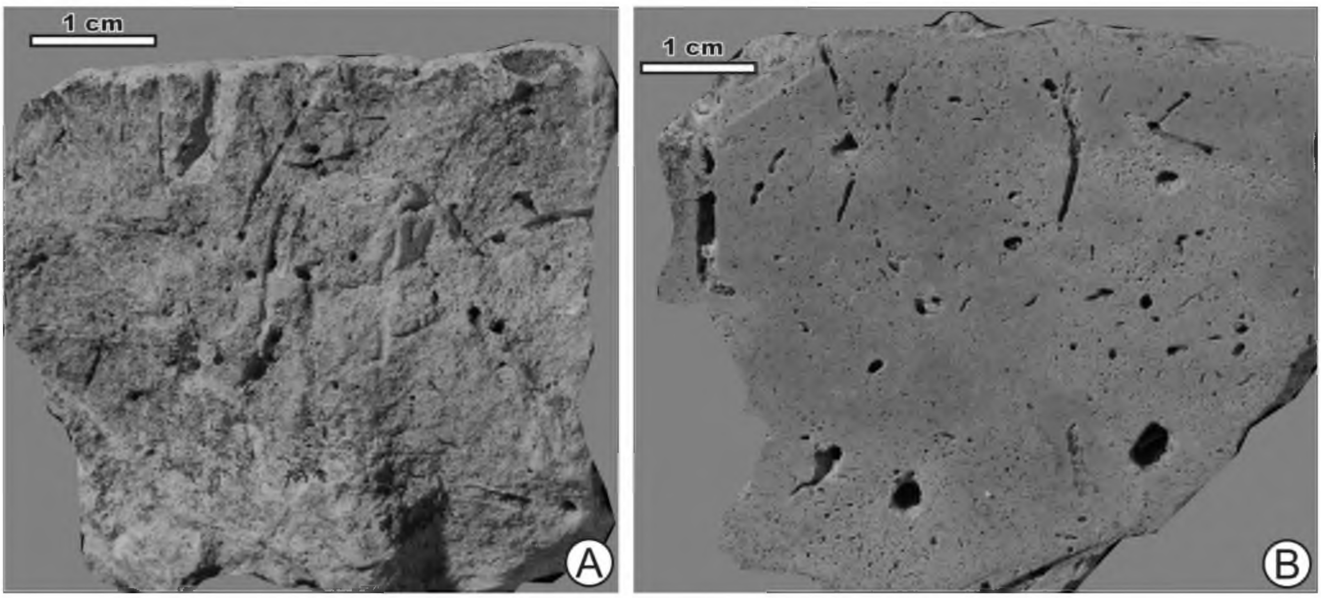


Fig. 9. Enigmatic void tubes in a calcareous siltstone sample from the lake-margin deposits at locality 2 (Fig. 1A), as seen at: **A** – Natural vertical section of sample, specimen 186P9; **B** – A similar polished section, specimen 186P10a

delta-derived turbidites were probably an important source of nutrient for the burrowers, as they are commonly draped with plant detritus.

The variegated marls with thin layers of micritic limestone in the lake-margin embayment indicate a very shallow and probably brackish subenvironment, where the calcareous background sedimentation was punctuated by relatively weak storm-wave action (i.e., an impact of storm waves breaking offshore). The tempestites here are thin and finer grained, commonly silty. The pre-event ichnofauna in these deposits is represented by the oblique cylindrical traces, whereas the large tubular structures, the planar wall structures and various other bioturbation features are post-event colonization traces. The bioturbation features are well visible in the muddy cappings of tempestite sandstone beds and in the graded silty marlstone beds attributed to the fallout of storm-derived suspension clouds. The homogeneous nature of inter-event marlstone layers can be due to a pervasive bioturbation of the soft and loosely packed calcareous sediment.

The *Vagorichnus* in the present case is undoubtedly a subaqueous feature, and its occurrence in the lake-interior deposits can be attributed to the relative shallowness of the Ermenek lake (see the earlier section on the lake conditions). The shallow lake bathymetry may have allowed a wider spread of fauna, whose distribution in a deeper lake might be limited to the lake nearshore zone.

All the trace fossils in the Ermenek lacustrine succession were apparently produced under water, and hence fall theoretically in the *Mermia* ichnofacies. This ichnofacies (Buatois & Mángano, 1995) is typical of siliciclastic, oxygenated lacustrine sediments deposited under a permanent cover of water, irrespective of the water depth. *Mermia* is characterized by a predominance of horizontal or sub- horizontal grazing and feeding traces produced by mobile sediment-feeders, subordinate locomotion traces, generally high to moderate ichnodiversity and abundance, and a low degree of specialization of grazing pattern (Buatois & Mángano, 1998). The Ermenek lake was characterized by a mixed siliciclastic-calcareous sedimentation, with the siliciclastic deposits derived mainly by storm events and the carbonates deposited periodically as a part of the "background" sedimentation. Not all features diagnostic of *Mermia* ichnofacies are observed here. Although there is a predominance of horizontal to subhorizontal, poorly specialized grazing and feeding traces, their diversity and abundance are relatively low. The ichnofauna diversity is similar to that in the Early Cretaceous lacustrine carbonates at Las Hoyas, Central Spain, where the trace-fossil assemblage was defined as an impoverished *Mermia* ichnofacies and attributed to poor lake-floor oxygenation (Buatois *et al.*, 2000).

Accordingly, the trace fossil assemblage of the Ermenek lake can similarly be classified as an impoverished *Mermia* ichnofacies and attributed to an environmental stress, although the stress factor in the present case may not have been strictly the same. The lake's bottom water was most probably hard, acidic, rich in CO_2 and poor in oxygen (see the earlier discussion of the lake conditions), but the lake floor was subject to brief oxygenation due to the episodic storm-wave action and incursions of river-derived turbidity currents. The lake was not evaporitic, but its chemical conditions periodically oscillated in this direction. Notably, the bioturbation zones at the top of tempestite beds are a few centimetres thick (Fig. 8A), unlike those in the Spanish Teruel Basin, where only very shallow or surficial trace fossils occur (Buatois *et al.*, 2000). The trace fossils in the Spanish evaporitic lakes (Rodríguez-Arnanda & Calvo, 1998) are even less diverse than in the present case and represent a much more impoverished *Mermia* ichnofacies (*cf.* Uchman & Álvaro, 2000).

Trace fossils are well recognizable at the tops of tempestite beds (Fig. 8A, B), where the fine-grained bioturbated layer is commonly 20–25 mm thick and the tiering pattern appears to have been "frozen". This layer passes gradually upwards into a massive layer, 30–40 mm thick, whose homogeneous nature can be attributed to the lower rate of suspension fallout and a pervasive bioturbation of surficial watery sediment (soupground). This sediment layer would have a negligible shear strength and bioturbation structures could thus be totally obliterated. Delicate structures could also be erased further by carbonate diagenesis. A similar pattern of bioturbation is observed, for example, in muddy deep-sea deposits, where a homogenized, mixed surficial layer overlies a transitional layer with distinct burrows produced in deeper tiers in an already slightly dewatered mud (Ekdale & Berger, 1978; Berger *et al.*, 1979; Ekdale *et al.*, 1984; Bromley 1990, 1996 and references therein). The present study shows that an analogous style of bioturbation, with mixed and transitional layers, is recognizable in lacustrine deposits.

CONCLUSIONS

1. Trace fossils in the Early Miocene siliciclastic-calcareous deposits of the Ermenek Basin can be classified as an impoverished *Mermia* ichnofacies.

2. The impoverishment of ichnofauna is attributed to the fluctuating chemistry of the lake water, with episodes of brackishness and periodic carbonate precipitation. The marl lake was not strictly evaporitic, but its hard-water conditions tended to shift in this direction, resulting in an increased salinity and unusual water chemistry. The lake's bottom water was acidic, poor in oxygen and supersaturated with carbon dioxide, but was episodically oxygenated by storms and turbidity currents, which also supplied plant detritus.

3. The lake was hydrologically closed and mainly no deeper than 10 m, agitated by frequent storm events and dominated by the deposition of tempestites. Delta-derived turbidites were common along the basin's southwestern margin, but only sporadically spread across the lake interior.

4. A second known occurrence of the ichnogenus *Vagorichnus* has been recognized, also here in a lacustrine environment, but in the lake interior area.

5. The lacustrine tempestites show pre- and post-event trace fossils, as observed in marine offshore-transition environments, although the trace-fossil content here is different.

6. The lacustrine deposits show recognizable couplets of mixed and transitional bioturbation layers, similar to those observed in many fine-grained deep-marine sedimentary successions.

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